



Aditya-L1 - An Observatory Class Mission: Spacecraft, Mission, and Operations

Nashiket Premal Parate¹ · Nigar Shaji¹ · Motamarri Srikanth¹ ·
K. Sankarasubramanian^{1,2} · Narashimha Murthy Patnaik¹ · S. Narendra¹ ·
Abhijit Avinash Adoni¹ · Kuldeep Negi¹ · Pragyan Pattanaik¹ · Bharat Kumar G. V. P¹ ·
Vivek R. Subramanian¹ · Hemanth Kumar Reddy N.¹ · Shree Niwas Sahu¹ ·
Vishnu Kishore Pai¹ · Sajjade Faisal Mustafa¹ · Richa Pathak³ · Amit Maji⁴ ·
T.R. Haridas⁵ · Anand Raj⁶ · Pankaj Agarwal⁷ · Arvind Kumar Singh¹ ·
Smruti Ranjan Panigrahi¹ · A. Ravi¹

Received: 5 January 2025 / Accepted: 10 August 2025
© The Author(s), under exclusive licence to Springer Nature B.V. 2025

Abstract

Aditya-L1 is an observatory class mission designed and developed by the Indian Space Research Organisation (ISRO) to study the Sun and the inner heliosphere. Aditya-L1, currently orbiting around the first Lagrange point L1, is in a periodic halo orbit located approximately at 1.5 million km from Earth on the Sun–Earth line (about 1% of the Sun–Earth distance and closer to Earth). The orbital parameters of Aditya-L1 around L1 are $A_x = 208,951$ km, $A_y = 670,024$ km and $A_z = 120,000$ km, where A_x , A_y and A_z are semi-diameters of the orbit with an orbital period of 177.86 days. The primary objective of the Aditya-L1 mission is to understand the coronal and chromospheric dynamics of the Sun along with its influence on the heliosphere, especially at the L1 location. To achieve these goals, the spacecraft is configured to accommodate seven payloads of which four are remote sensing and three are in situ experiments. The scientific payloads are designed and developed by various Indian Research Institutes in close collaboration with different ISRO centers. The spacecraft is configured with the modified Mars orbiter mission (MOM) bus and is a three-axis stabilized spacecraft with a lift of mass of 1480.73 kg and power generation of ≈ 1820 W. Pointing stability will be better than 15 arcsec as required by the coronagraph payload. Aditya-L1 payload produces around 240 Gbits of science data per day ($\approx 90\%$ data is from the imaging payloads). Planning, coordination, and operation of the spacecraft and the scientific payloads are conducted from ISRO telemetry, tracking, and command network in Bengaluru, India. Aditya-L1 was launched on board the Polar Satellite Launch Vehicle (PSLV C57) at 11:50 Indian standard time (IST) from the second launch pad of the Satish Dhawan Space Centre (SDSC), Sriharikota, India on 2 September 2023. It was inserted at the L1 point on 6 January 2024, at 4:17 pm IST. The spacecraft, mission, and operation aspects of the Aditya-L1 spacecraft are discussed in this paper.

Keywords Aditya-L1 · Solar atmosphere · X-rays from the Sun · Near ultraviolet solar images · Solar flares · Solar dynamics · Solar electron · Solar ions · Magnetic field at L1 · In situ measurements of solar plasma

Extended author information available on the last page of the article

1. Introduction

The Sun is a very dynamic star that extends far beyond the visible surface. It shows several eruptive phenomena and releases immense amounts of energy during those eruptions to the solar system. If an explosive solar phenomenon is directed towards the Earth, it could cause various types of disturbances in the near-Earth space environment. The Sun has been studied extensively in great detail, both spatially and temporally, as it is our nearest star. It has been observed for over 300 years and solar physics has attained the status of a mature and independent discipline in astrophysics. Although both observations and modeling have improved tremendously over the years, there are still a number of outstanding scientific questions that remain unanswered. For several decades, the puzzle of what sources heat the chromosphere, the transition region, and the solar corona, above the much cooler photosphere, still remains an enigma. Similarly eruptive phenomena like flares and coronal mass ejections (CMEs), which expel huge amounts of particles and electromagnetic energy into interplanetary space and which have direct space weather consequences on the Earth, are still difficult to comprehend and forecast. In an attempt to unravel some of these mysteries, the Aditya-L1 mission, an Indian dedicated solar and heliospheric observatory at Lagrangian point L1, is configured to obtain a better understanding of the physical processes of the outer layers of the Sun and its influence at L1. The mission is designed for a lifetime of 5 years. The spacecraft is configured on the modified Indian Mars orbiter mission bus with a lift of mass of around 1480.73 kg and power generation of ≈ 1820 W (Arunan and Satish 2015). The spacecraft is configured with seven payloads for its scientific studies, namely,

- Visible Emission Line Coronagraph (VELC; Singh et al. 2025) for the study of dynamical events in the solar corona like coronal mass ejections,
- Solar Ultraviolet Imaging Telescope (SUIT; Tripathi et al. 2025) for the study of the lower and middle solar atmosphere including the dynamical events like solar flares and prominence eruptions,
- Solar Low Energy X-ray Spectrometer (SoLEXS; Sankarasubramanian et al. 2025a) and High Energy L1 Orbiting X-ray Spectrometer (HELIOS; Nandi et al. 2025) to study the dynamical events like solar flares in the solar corona using Sun-as-a-star,
- Aditya Solar wind Particle Experiment (ASPEX; Goyal et al. 2025 and Kumar et al. 2025) for the study of solar energetic particles especially protons and alpha particles,
- Plasma Analyser Package for Aditya (PAPA; Thampi et al. 2025) for the study of the composition of the solar wind and the energy distribution for electrons and energetic ions, and
- Magnetometer (MAG; Yadav et al. 2025) on a deployable boom to study the nature of the Interplanetary Magnetic Field (IMF).

The two images on the left of Figure 1 show the Aditya-L1 satellite in a stowed configuration, while the right image shows the deployed configuration. Figure 2 shows the Aditya-L1 after integration with the adopter of the polar satellite launch vehicle (PSLV). In the following sections, we will summarize the mission aspects, spacecraft configuration, scientific payload details, and ground segment.

2. Mission Overview

2.1. Mission Objectives

Aditya-L1 mission is driven by the following primary scientific objectives (Seetha and Megala 2017):

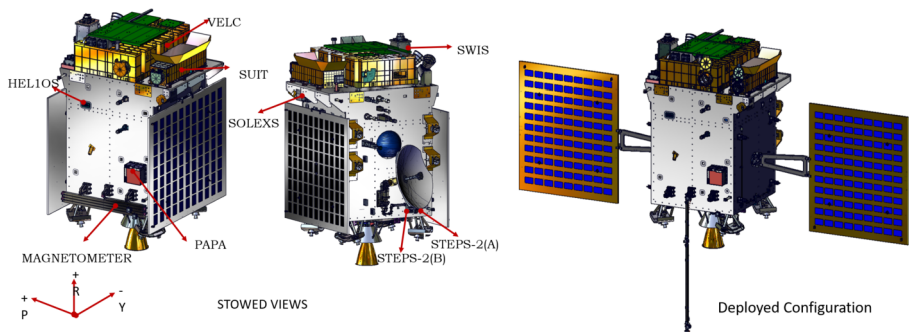
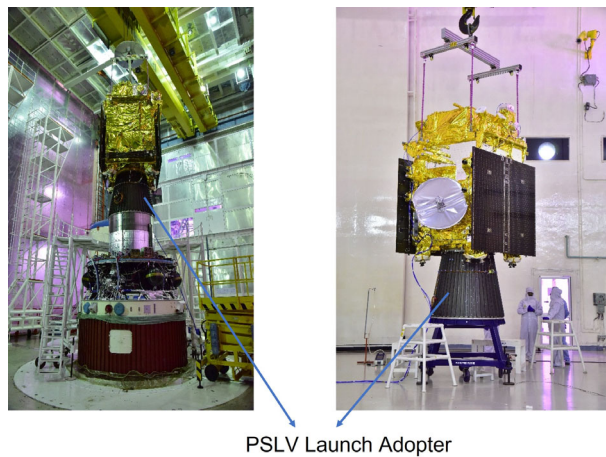


Figure 1 Left: Stowed configuration of Aditya-L1. Mounting locations of payloads are marked. Right: Deployed configuration of Aditya-L1. Boom deployment of the Magnetometer was carried out at the Sun-Earth L1 point.

Figure 2 Aditya-L1 integrated satellite along with the Polar Satellite Launch Vehicle (PSLV) adpter.



- Study of the solar upper atmospheric dynamics, especially the chromospheric and coronal regions.
- Study of chromospheric and coronal heating, physics of the partially ionized plasma, initiation of coronal mass ejections and flares.
- Observe the in situ particle, plasma, and magnetic environments that provide data for the study of particle dynamics at L1 as well as its source regions on the Sun.

To attain the above objectives, a set of technical elements/parameters for the spacecraft were identified for both the space and ground segments. These include the orbit parameters, payloads, spacecraft mainframe, the telemetry, tracking, and command (TTC) station network for mission operation, and data reception/processing facilities. The main mission specifications of Aditya-L1 are given in Table 1. The experiments on Aditya-L1 demand high pointing and stability of the platform and the specifications for these parameters are dictated by the respective payloads as mentioned in Table 1.

Table 1 Major mission specification of Aditya-L1.

Mission life	5 years.
Launch mass	1481 kg.
Launch vehicle	Polar Satellite Launch Vehicle (PSLV XL).
Orbit	Halo orbit class-1.
Spacecraft attitude at L-1	Sun pointing.
Pointing accuracy (defined by VELC)	< 0.0084 deg (30 arcsec) at 3σ .
Stability (defined by VELC)	$< 7.0 \times 10^{-5}$ deg/sec (0.25 arcsec/sec).
Jitter (defined by SUIT)	< 0.5 arcsec at 3σ .
Power generation	1820 W.
Mission control, data processing, and dissemination	Indian space science data centre (ISSDC) and ISRO tracking, telemetry, and command network (ISTRAC).
Tracking support	Indian Deep Space Network (IDSN), Bengaluru, and Deep Space Network (DSN), ESA.
Key requirements for Telemetry (TM):	
Number of TM downlinks	2 (TM1/TM2),
TM modulation	Pulse code modulation (PCM)/binary phase shift keying (BPSK).
TM normal bit rate	1000/500/250kbps with 32 kHz carrier, turbo coding.
TM format	Consultative committee for space data systems (CCSDS) Version 1.
On board timer resolution	125 micro-second.
Telecommand (TC):	
Number of uplinks	2.
Modulation	PCM/phase shift keying (PSK)/pulse modulation (PM).
Sub-carrier	16 kHz.
Bit rate	125 bps.
Format	CCSDS packet format.
Payload operation centre (POC)	POC processes the payload data into higher level science ready data as Level-1 and above. Payload POCs are in: VELC, Indian Institute of Astrophysics (IIA); SUIT, Inter-University Centre for Astronomy and Astrophysics (IUCAA); SoLEXS and HELIOS, U R Rao Satellite Centre (URSC); PAPA and MAG, Space Physics Laboratory (SPL); ASPEX, Physical Research Laboratory (PRL).

2.2. Selection of Halo Orbit Around the Sun-Earth L1

The halo orbit around the Sun-Earth L1 point provides distinct advantages compared to Low Earth or Geo orbits (LEO or GEO) in studying the Sun and the solar disturbances directed towards the Earth. Some of the advantages are listed below:

1. The L1 orbit provides continuous visibility for solar observations without any eclipses.
2. The L1 orbit is outside the Earth's magnetosphere, allowing observations of pristine charged particles from the Sun including solar events such as flares and coronal mass ejections (CMEs) and the in situ interplanetary magnetic field.

Table 2 The orbital parameters of Aditya-L1 satellite at the Sun-Earth Lagrangian point L1.

Az (km)	Ax (km)	Ay (km)	Time period (days)	Minimum SEV angle (degree)	Maximum SEV angle (degree)
120,000.5	204,707.5	670,024.1	178	4.86	25.81

3. X-ray payloads can be operated continuously with a stable background except during the solar energetic particle (SEP) passage.
4. Long continuous visibility of the satellite.

The selection of the halo orbit depends on various mission constraints: Sun Exclusion Zone (SEZ), gimbal limits of the on board steerable antenna, beam width of the antenna, scientific requirement, and optimal insertion cost. The primary mission constraints placed on the halo orbit selection are the following:

- The minimum Sun-Earth spacecraft angle (Sun-Earth-Vehicle, SEV Angle) should never be less than 4.5 degrees. The minimum SEV angle constraint satisfies the Solar Exclusion Zone (SEZ) requirement (the spacecraft must skirt the SEZ to avoid solar interference with communication).
- The maximum SEV angle should never be greater than 26 degree. The maximum SEV angle constraint derives from the gimbal angle limits of the high gain antenna (HGA) dish used for communication with the Earth.

Based on the above, the designed orbital parameters of Aditya-L1 are achieved and provided in Table 2.

3. Space Segment

The Aditya-L1 space segment is essentially configured around a three-axis body-stabilized spacecraft to carry the seven scientific experiments and the necessary mainframe systems to support payload operations. The major elements of the spacecraft are shown in the exploded view in Figure 3 along with the overall configuration of the spacecraft in Figure 4.

The spacecraft configuration is a balanced mixture of design from flight proven Indian Remote Sensing (IRS)/Indian National Satellite System (INSAT)/MOM bus. A brief description of the various sub-systems of the spacecraft is given below and parts of each sub-system are listed in Table 3.

3.1. Structure

The Aditya-L1 platform is cuboid similar to the MOM structure (Arunan and Satish 2015). The thrust cylinder and shear webs are of honeycomb sandwich construction with CFRP face sheet and the aluminium honeycomb core. All other sandwich decks are of aluminium face sheet and aluminium core. The unidirectional (UD) carbon fiber M55J impregnated with a resin epoxy EX1515 system and bi-directional (BD) fabric with M60JB fibers impregnated with EX1515 resin systems are used for cylinders. Unidirectional (UD) carbon fibre M55J impregnated with M18 resin epoxy and M18/43090 fabric are used in various components.

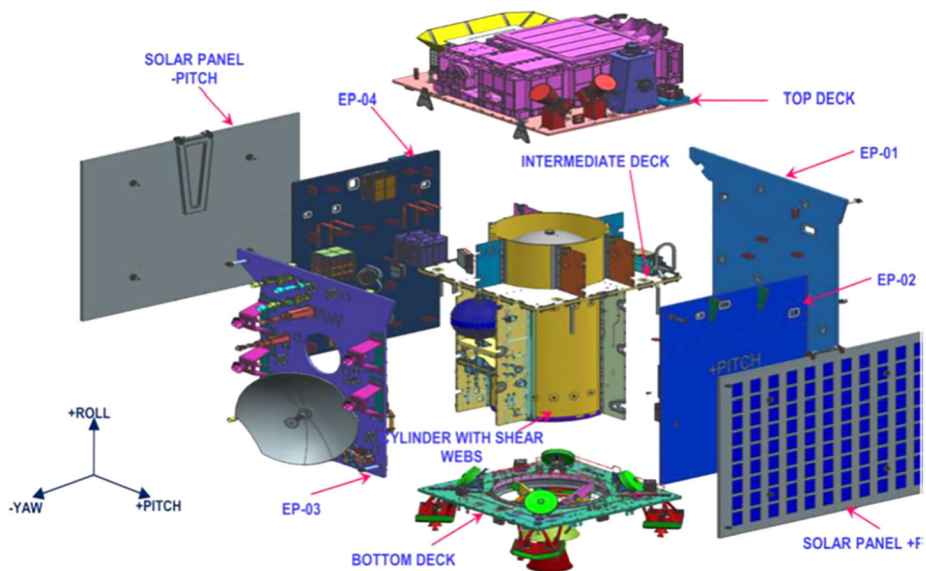


Figure 3 Aditya-L1 satellite exploded view with major elements marked. Note: The yaw, pitch, and roll marked in this figure are not connected to the A_x , A_y , and A_z amplitudes mentioned in the orbit coordinate system.

3.2. Thermal Control System

The thermal control system includes both a conventional passive control system and a ground/auto controlled active heater control system. The thermal design ensures that temperatures of all subsystems remain within specified limits in all phases of the mission. The thermal environment specification (TES) defines the operating boundary conditions for each package. The thermal design aims to maintain temperature of a given subsystem or unit within its thermal design temperature range.

The passive thermal control system augmented by heaters (that compensate for excess cooling by design or during contingency conditions) is adopted for the Aditya spacecraft. TES comprises a temperature specification and a space thermal environment. The space environment for the internal package is part of the temperature specification. The radiative thermal environment, experienced by appendages and external surfaces of the spacecraft, in various mission phases was considered during the evolution of the thermal design. New technologies/methods used in the thermal systems are,

- The cooling system for on board detectors (VELC, SUIT, and HELIOS) use special temperature sensor processing and heater controllers that enable fine temperature control in imaging mode and coarse temperature control in storage mode.
- Application of mini-heat pipes (mHP) to route heat from the detector are the first in this spacecraft.
- The thermal design and analysis of SUIT thermal filters that dissipate energy outside the wavelength band of SUIT. The measured spectral response properties of the filters are used to calculate their radiative properties, which are later used to estimate the steady-state temperature distribution attained in the filters. These values are used for the qualification range for these filters.

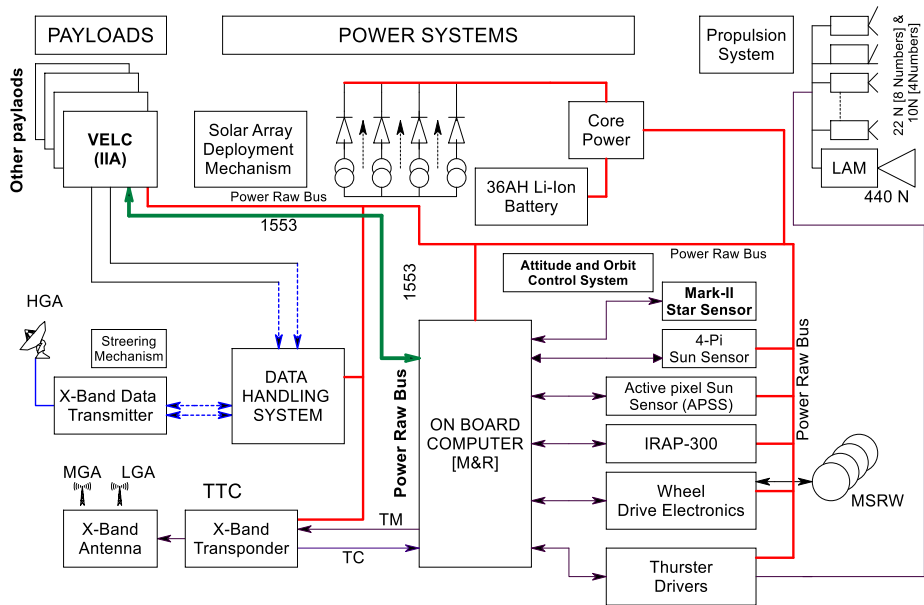


Figure 4 Aditya-L1 overall functional configuration of the satellite.

3.3. Spacecraft Mechanisms

The spacecraft has various deployable mechanisms for both the bus elements and the payloads.

3.3.1. Solar Array Deployment Mechanism (SADM)

Aditya-L1 has two deployable solar arrays each consisting of a single panel and yoke on the EP02 and EP04 side deck of the spacecraft. The arrays are deployed immediately after spacecraft injection by cutting the hold down loop using a pyro cutter.

3.3.2. Solar Panel Drive Mechanisms (SPDM)

The solar array of Aditya-L1 needs to be rotated ± 175 degree from the initial deployed configuration (cell facing +yaw direction). In L1 orbit the requirement for the tracking of the Sun is minimal as the mission is planned with the +yaw side of the spacecraft always pointing towards the Sun.

3.3.3. High Gain Antenna Steering Mechanism (HGASM)

The high gain antenna mechanism is required for downlinking of payload data to the ground stations. This mechanism is meant to steer the antenna along the given profile to give a full coverage for near real time data transfer.

Table 3 Subsystems of the spacecraft.

Subsystem	Main Features
Structure	Modified I 1.5 K bus (similar to MOM)
Thermal control system	Passive (OSR, MLI, mini heat pipe), heaters, and radiator plates.
Spacecraft mechanisms	Solar panel deployment mechanisms, solar panel drive mechanism (SPDM), high gain antenna steering mechanism, VELC and SUIT motorized multi-operation, cover mechanism, VELC precision linear micro scanning mechanism, VELC deployable exit cover mechanism, SoLEXS payload mechanism, 6 meter deployable magnetometer boom, SUIT filter wheel mechanism, VELC retarder mechanism, SUIT shutter mechanism, SUIT focus correction mechanism.
Propulsion system	8 numbers of 22 N thrusters, 1 number of 440 N LAM (area ratio of 250) engine, Bi propellant of 595 kg, 4 numbers of 10 N thruster.
Power system	30–42 V single bus, digital taper charge regulator (TCR) based, and modular MOSFET based EED power unit (MEPU), two rigid panels with advanced triple junction (ATJ) cells for ≈ 1820 W generation at end of life (EOL), and 35 Ah Lithium-ion battery.
On board computer (OBC)	LEON-3 UT699 at 48 MHz processor based system.
Attitude and orbit control system (AOCS)	Precision active pixel sun sensor (APSS); 4- π sun sensors, 2 numbers of star sensors (Mk-II), solar panel sun sensor (SPSS), inertial referencing and positioning system (IRAP-300), 4 reaction wheels with magnetic suspension (angular momentum of 15 Nms), 8 numbers of 22 N thrusters, 1 number of 440 N LAM, 4 numbers of 10 N thruster, pointing accuracy of 15 arc sec at 1σ , and drift rate of < 0.18 arc sec/s ($< 5 \times 10^{-3}$ deg/s).
X-band telemetry and telecommand (TTC) transponder system	Telecommand at 125bps with 8 kHz sub carrier, BCH coding with cyclic redundancy check (CRC), and CCSDS. Telemetry at 1024 bits per sec (bps)/512 bps/256 bps with 32 kHz sub carrier, turbo coding, and CCSDS.
X-band data transmission system	TC (uplink) – F1: 7219.611 MHz, F2: 7232.531 MHz (X-Band), CCSDS, TM (downlink) - F1: 8482.32 MHz, F2: 8497.50 MHz (X-Band), and data (downlink)- 8460 MHz.
On board data handling and storage system (ODHS)	RS + TCM with 8 PSK using three 4 Mbps chains (I,Q,C) with data rate of 12 Mbps, RS + QPSK using two 4 Mbps chains (I,Q) with 8 Mbps data rate, and solid state recorder (SSR) is of 650 Gbits size at EOL.

3.3.4. Motorized Cover Mechanism for VELC and SUIT Payload

The entry of the telescopes is covered with circular aluminum plates which need to be opened or closed. The covers are provided for protecting the optical elements from contaminants present in the atmosphere on ground. The covers are opened for observations after reaching the L1 orbit. The covers need to be closed to protect the optical elements during thruster and safe mode operations of the spacecraft. The closed configuration is also used for calibration. This multi-operation door mechanism is tested for more than 500 operations for its life test.

3.3.5. VELC-Precision Linear Micro Scanning Mechanism

The precision linear scan mechanism (PLSM) works on the principle of converting the rotary motion to linear motion with the help of a preloaded ball screw mechanism. The linear scan mechanism is used to move the image of the Sun on the spectrograph slit to cover the required field of view (FOV) in a controlled manner with a precision of better than few micrometers.

3.3.6. VELC- Deployable Exit Cover Mechanism

An exit baffle is provided on VELC payload to reject the disk light of Sun, out of the payload. The disk light is ejected out of the VELC payload at an angle 90 degree to that of its optical axis.

3.3.7. VELC- Retarder Mechanism

The retarder mechanism for VELC payload for Aditya-L1 project is designed to hold and rotate the retarder optics at a constant rotation speed. The rotation of the retarder is enabled during the spectro-polarimetric observation mode in VELC.

3.3.8. SoLEXS Payload Mechanism

The general functional requirements for the SoLEXS payload mechanism are:

- Cover the aperture/holes during ground/launch and deploy in L1 orbit.
- The deployed shutter to clear the FOV of SoLEXS.

This mechanism is required to protect the detectors of SoLEX from degradation during the spacecraft passage in the Earth orbit phase of the mission.

3.3.9. Six-Meter Deployable Magnetometer Boom

To avoid the effect of the ambient spacecraft magnetic field, the two sensors of approximately 150 grams mass are mounted on a non-ferrous deployable boom, which can be stowed on to the spacecraft during launch and deployed in orbit. An accordion type deployment is employed to minimize the dynamic loads due to deployment. Positive locking at the end of deployment is provided by means of a pawl lock mechanism.

3.3.10. SUIT Filter Wheel Mechanism

The SUIT payload has a total of 11 science filters (eight narrow band and three broadband filters) which will be mounted on two filter wheels each with eight filter slots (total 16 slots). The other five slots will have four neutral density filters (which are identical in mass and effective thickness to science filters) and one closed position for taking dark frames. A combination of filters has to be introduced into the beam path by simultaneous operation of the filter wheels as per a pre-defined sequence. Two independent filter wheel drive mechanisms, capable of moving the required filters to the desired location on command, are used in SUIT payload.

3.3.11. SUIT Shutter Mechanism

The vane shutter is the shutter used to control the exposure time for the SUIT payload. It consists of a vane which has open and closed regions. The light will be allowed to pass towards the imaging detector during the open phase, and blocked during the closed phase. The image will reach the CCD detector during the open phase, and the CCD will be read out by associated electronics during the closed phase.

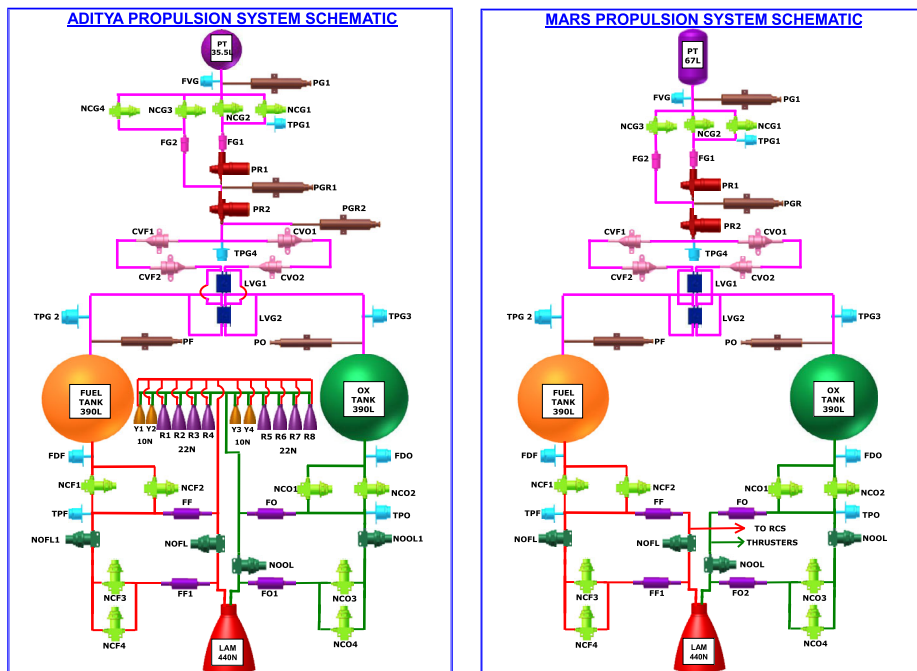


Figure 5 Comparison of the propulsion system used in MOM and Aditya-L1.

3.3.12. SUIT Focus Correction Mechanism

The focus correction of SUIT payload with the focusing mechanism can be carried out in case the image defocus is established during the payload verification phase of the mission.

3.4. Propulsion System

The spacecraft adopts a bi-propellant system to carry it from a geo-transfer orbit to the L1 orbit, including orbit and attitude maintenance in the L1 orbit. The spacecraft propulsion subsystem is designed for attitude and orbit control during different phases of the mission and orbit raising operations such as transfer orbit, orbit raising to L1 orbit, station acquisition, station keeping, back up for momentum dumping etc.

The Aditya-L1 propulsion system is based on the heritage of the MOM propulsion system. Figure 5 shows a comparison with the MOM and Aditya-L1 propulsion system. The Aditya L1 mission has the following changes compared to MOM to meet the mission requirements.

- One 35.5 litre indigenous pressurant tank in lieu of 67 litre imported tank.
- One additional normally closed (NC) gas pyro (NCG4) for redundancy.
- One additional pressure monitoring in between the pressure regulators PR2 and check valve.
- 4 numbers of 10 N thrusters for station keeping manoeuvre.
- Inclusion of PLO and PLF pressure transducers.

3.5. Power System

The Aditya-L1 spacecraft electrical power subsystem (EPS) provides generation, storage, control, and distribution of unregulated power for the operation of all subsystems and components. It is a direct energy transfer system, which converts solar energy into electrical energy and provides it directly to all loads at an unregulated voltage that varies from 30 V to 41.5 V. Energy balance, battery charge, and discharge control, power safety and ground spacecraft checkout power interfacing are all functional elements of the power system.

The electrical power system of Aditya-L1 is a single bus direct energy transfer system configured to meet the spacecraft peak load demand of around 1550 W including battery charging, eclipse load of 888 W (only during transfer orbit phase) over the life of the mission, which is five years or more.

The power generation is accomplished by rigid and deployable solar array having two wings, populated with an advanced triple junction (ATJ) solar cells with 30.5% efficiency. A total of 30 solar array strings are connected in parallel to form a bus.

The energy storage supports eclipse and peak electrical load requirements in excess of generation. It is achieved by a single Li-ion battery system with capacity of 35 Ah (using 3.5 Ah LG commercial off-the-shelf (COTS) cells). The spacecraft power is distributed by a single bus, which is formed by connecting in parallel, both the wings of the solar array with a battery. The power bus control is an FPGA based regulator which takes care of bus regulation and battery charging. The power system is configured to handle conditions like under voltage, over discharge, and over charge.

3.6. On Board Computer (OBC)

The on board computer (OBC) flown on Aditya-L1 is the third version (V3) of the OBC which was used for Meghatropiques (Raju 2013) and RISAT missions (Valarmathi and Tyagi 2013). The upgrading in this version includes a LEON-3 processor, CCSDS based telecommand with optional encryption, and CCSDS based telemetry with turbo encoding.

The LEON-3 based OBC-V3 in Aditya-L1, integrates the functions of AOCS, sensor electronics, CCSDS based telecommand, CCSDS based telemetry and thermal management with that of the spacecraft either through standard interfaces or through MIL-STD-1553B. The LEON-3 based OBC-V3 is designed using a combination of OBC ASIC (application specific integrated circuit) and FPGAs (field programmable gated arrays). The analogue logics and driver circuits are realized using HMCs (hybrid micro-circuits). Since OBC is the heart of the spacecraft, separate main and redundant packages are included for carrying out OBC functions to take care of any failures.

The salient features of OBC-V3 on Aditya-L1 include increased performance, reduced execution time, miniaturization, standardization of interfaces, and improved autonomy. The OBC-V3 developed for Aditya-L1 is also implemented for the GISAT-1 mission of ISRO.

3.7. Attitude and Orbit Control Systems (AOCS)

The attitude and orbit control system (AOCS) is the main system responsible for the precise attitude and orbit maintenance of the spacecraft. It consists of high precision star and Sun sensors to measure its attitude, control electronics, and actuators to correct for any deviation. The required AOCS specifications are the following:

- Pointing accuracy of the spacecraft: 0.0083 deg (30'') at 3σ
- Alignment accuracy for payload (for VELC): 0.0042 deg (15'')

- Stability of the spacecraft: $< \pm 7.0 \times 10^{-5}$ deg/sec

The internal occulter size of the coronagraph is $0.05 R_{\odot}$ (where $R_{\odot}$ is radius of the Sun) which is 48 arcsec (for 16 arcmin $R_{\odot}$). Hence, the overall pointing of the coronagraph payload should be better than 48 arcsec out of which 30 arcsec is provisioned for the spacecraft at 3σ and 15 arcsec for the alignment inaccuracies of the payload. Note that the alignment inaccuracies of the coronagraph can be overcome by giving an offset to the satellite.

3.7.1. Attitude Sensors

The sensor configuration is aimed to meet the attitude measurement requirements of initial attitude acquisition, three axes Earth-pointing mode, and for data product generation.

The sensor system configuration for Aditya-L1 consists of

- Star sensors (Mark-II): 2 numbers
- 4pi Sun sensors: 4 numbers
- Solar panel Sun sensors: 4 numbers
- High-Accuracy Active Pixel Sun Sensor: 2 numbers
- Temperature sensors: fine temperature sensor (FTS), platinum resistor thermometer (PRT), and thermistors

3.7.2. Magnetically Suspended Reaction Wheels (MSRW)

A magnetically suspended reaction wheel (MSRW) with higher angular momentum and a low torque noise is adopted for Aditya-L1. The reaction wheel assembly comprises four MSRW of 15 Nms momentum and 0.1 Nm torque capacity along with a four single channel wheel drive electronics (WDE). Four reaction wheels are mounted in a tetrahedral configuration so that its reaction torque resolves about all the three spacecraft axes providing the required torque for attitude control and redundancy management in case of any one reaction wheel failure. The WDE interfaces between the other satellite subsystems and all the four reaction wheels for active attitude control of the satellite. The WDE interfaces with power, attitude and orbit control electronics (AOCE), TM, and TC to carry out its functionalities.

3.7.3. Inertial Referencing and Accelerometer Package (IRAP-300)

The inertial referencing and accelerometer package (hereafter referred as IRAP-300) provides the incremental angle and accumulated ΔV along the three principal spacecraft axis with redundancy. The IRAP-300 package consists of three numbers of dynamically tuned gyros (DTGs) along the roll, pitch, and yaw axes in an orthogonal configuration and four numbers of ceramic servo accelerometers (CSAs) in an octahedral tetrad with skew angle of 45° with +roll axis of Aditya-L1. The IRAP-300 package measures the incremental velocity imparted to the spacecraft along the roll, pitch, and yaw axes and effects on board termination of firing upon achieving the required ΔV . The sensors in IRAP-300 package are mounted on a vibration-isolated cluster and the cluster temperature is controlled to obtain stable performance. The IRAP electronics for the DTGs is based on 32-bit RadHard Atmel AT697F processor and Actel RTSX72 FPGA.

3.7.4. Thrusters for AOCS

The Aditya-L1 mission requires high pointing accuracy and stability in the halo phase. During nominal payload operation after halo-orbit insertion at the L1 point, the spacecraft will

be in a normal mode of operation and wheels will be used for attitude control. In L1 orbit, the major source of disturbance is the solar radiation pressure (SRP) which induces a disturbance torque about the body and changes the total angular momentum. Continuous external disturbances result in the increase or decrease of reaction wheel speeds. Since there is a limit on the range of operation of wheel speeds, they have to be brought down by external torquing. As there are no magnetic torquers in Aditya-L1, momentum dumping (MD) of the reaction wheels is only achievable by thrusters. Momentum dumping would not only introduce ΔV in the roll axis, which is in-plane for the halo orbit and is undesirable from the orbit perturbation point of view. Additionally, thrusters will be used for station keeping (SK) manoeuvres to maintain periodicity of the halo orbit. Based on analysis, SK manoeuvres are normally scheduled once every 3 months (half of the orbit period). Maximum orbit correction is required along +yaw direction (towards the Sun). The existing thruster configuration of Aditya-L1 consists of eight 22 N canted thrusters along the -roll and is used for attitude control and momentum management (similar to MOM). With the existing thrusters, a pitch rotation of 90 degrees is required before every SK manoeuvre to align the bottom deck thrusters along the Sun-Earth line. Also, ΔV along roll is imparted for momentum dumping (MD) pulses, which is undesirable from the orbit determination point of view. To meet the MD and SK requirements for Aditya-L1, four additional thrusters on anti-yaw (Earth viewing) face are considered. MD and SK manoeuvres can also be combined to ensure a minimum outage of payload science data.

Hence, the additional anti-yaw thrusters are required for:

- De-saturate reaction wheels without imparting ΔV along roll axis.
- Provide ΔV along yaw for orbit correction without rotating the spacecraft.

There are 12 thrusters in Aditya-L1 for attitude and orbit control and momentum management. Eight 22 N canted thrusters are mounted along -roll (similar to MOM). Four 10 N uncanted thrusters are mounted along -yaw (introduced for station keeping and momentum dumping in L1 phase).

3.8. X-Band TTC Transponder System

The X-band TTC radio frequency (RF) systems for the Aditya-L1 mission consist of two chains of phase locked loop (PLL) based coherent TTC Transponders with RF power output capability of 10 W for TM downlink, a near 100% omni-coverage individual antenna systems (low gain antenna and medium gain antenna) for uplink/downlink chains and associated feed networks. While the uplink and downlink modulation scheme for handling TC and TM data is PCM/PSK/PM, ranging is carried out by PM modulation. Mechanically, transmitter and receiver decks are stacked. The TTC system comprises subsystems such as antennas, receivers, transmitters, feed networks and filters to meet the following functional requirements:

- Phase-lock the transmitter downlink carrier to the uplink carrier at a precise frequency turn-around ratio of 880/749 to enable measurement of two-way Doppler.
- Phase demodulation of the on board received signal to extract the ranging signal (tone/pseudo-noise (PN) signal) and 8 kHz command PSK subcarrier which is further demodulated by a PSK demodulator to give data and clock as outputs for further processing in TC decoder.
- Either tone ranging or PN ranging support by the TTC system based on mission planning.
- Simultaneously transmit housekeeping telemetry and ranging signal (either tone/PN signal).

Table 4 Payload maximum data rate and storage requirement per day.

Payload	Maximum data rate	Mode	Data volume per day (Gbits)
VELC	52.5Mbps	Spectroscopy	105
SUIT	16 Mbps	Multiple	105
SoLEXS	12 kbps	Single	1
HEL1OS	4.13 Mbps	Flare	4
ASPEX	66 kbps	SWIS-flare mode	8
	192 kbps	STEPS	8
PAPA	24 kbps	Single	1.5
MAG	1 kbps	Single	0.5

3.9. X-Band Data Transmission System

The X-band data transmitter for Aditya-L1 mission accepts data from the baseband data handling (BDH) system at 3×4 Mbps, modulates it on the X-band carrier and amplifies it to the level required for transmission to the ground station. The modulation used is 8-PSK. Two identical data transmitters operating at 8460 MHz are configured in passive redundancy. The selection of main or redundant transmitter is done by ground command. The X-band data transmitter consists of: (a) carrier generator, (b) modulator, and (c) DC-DC decks housed together in a single package.

3.10. On Board Data Handling and Storage (ODHS)

BDH and SSR have been integrated into a single package named ODHS (on board data handling and storage). Both systems share common resources with respect to power and OBC interface. Both main and redundant systems are housed in the same package. Data from seven payloads, on board camera system, and auxiliary data (AOCE, GYRO, low bitrate telemetry, and TC history) are formatted suitably and stored in SSR before transmission to the RF system. Separate DC-DC convertors are used for the main and the redundant systems.

The solid state recorder (SSR) storage system handles three record streams of data from BDH. Chain1 data is recorded in an SSR of capacity 300 Gb. Chain2 and chain3 data are recorded in two partitions of SSR of size 260 Gb and 40 Gb, respectively. SSR provides two ports for play back (PB; SSR PB port 1: Chain1 data and SSR PB port 2: selected chain2/chain3 data). The details of each payload data rate and the storage requirement are given in Table 4.

3.11. Science Experiments on Board Aditya-L1

The instruments of Aditya-L1 are tuned to observe the solar atmosphere, mainly the chromosphere and corona. In situ instruments will observe the local environment at the L1 point. There are seven payloads on board Aditya-L1, with four for remote sensing of the Sun and three for in situ observation. The payloads have been developed by different laboratories in the country with close collaborations of various ISRO centres. These payloads are selected such that they provide complementary observations. Table 5 captures the major capabilities of these experiments. Detailed information about the experiments is available as separate papers in this volume and interested readers are suggested to read them.

Table 5 Aditya-L1 payloads and its capabilities.

Type	Payload and institution	Capability	References
Remote sensing payload	Visible Emission Line coronagraph (VELC), Indian Institute of Astrophysics (IIA), Bengaluru	Coronal imaging, spectroscopy, and polarimetry	Raghavendra Prasad et al. (2017), Singh et al. (2025)
Remote sensing payload	Solar Ultraviolet Imaging Telescope (SUIT), Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune	Photosphere and chromosphere imaging in narrow and broadband	Tripathi et al. (2017, 2025)
Remote sensing payload	Solar Low Energy X-ray Spectrometer (SoLEXS), U R Rao Satellite Centre, Bengaluru	Soft X-ray spectrometer: Sun-as-a-star observation	Sankarasubramanian et al. (2011, 2025a)
Remote sensing payload	High Energy L1 Orbiting X-ray Spectrometer (HELIOS), U R Rao Satellite Centre, Bengaluru	Hard X-ray spectrometer: Sun-as-a-star observation	Sankarasubramanian et al. (2011), Nandi et al. (2025)
In situ payload	Aditya Solar wind Particle Experiment (ASPEX), Physical Research Laboratory (PRL), Ahmedabad	Solar wind and particle analyzer: protons and alphas with directions	Janardhan et al. (2017), Goyal et al. (2025), Kumar et al. (2025)
In situ payload	Plasma Analyser Package for Aditya (PAPA), Space Physics Laboratory (SPL), Thiruvananthapuram	Solar wind and particle analyzer: electrons and heavier ions with directions	Janardhan et al. (2017), Thampi et al. (2025)
In situ payload	Advanced tri-axial high resolution digital magnetometers, Laboratory for Electro-optics Systems (LEOS), Bengaluru	In situ magnetic field (Bx, By, Bz)	Janardhan et al. (2017), Yadav et al. (2025)

It is also important to emphasize that Aditya-L1 with its unique capabilities can provide synergy with other contemporary missions. Potential applications of such synergetic observations are provided in Sankarasubramanian et al. (2025b). With many new missions slated to be launched in 2025, it is important to carry out joint observing campaigns to leverage better science.

4. Ground Segment

Aditya-L1 mission operations will be supported for a mission life of five years through IS-TRAC and its ground station network. The ground segment elements include the spacecraft control centre (SCC) at ISTRAC, the Indian deep space network (IDSN) and, the Indian

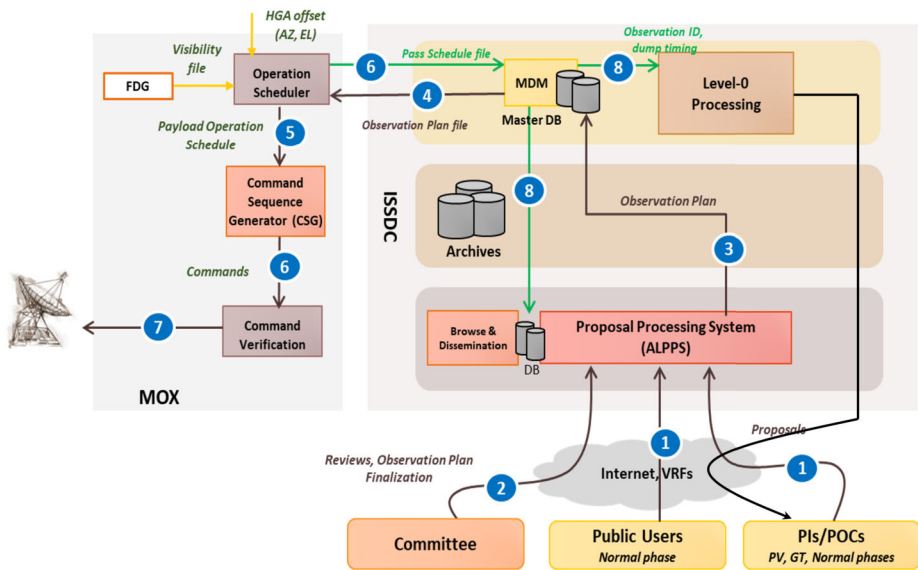


Figure 6 Interface between ground segment elements.

space science data centre (ISSDC). The existing TTC network of ISTRAC supports the TTC functions. For the initial phase of operations, the network has been augmented with additional network stations from other agencies. The payload data are acquired through IDSN. The payload data are processed and disseminated through ISSDC. The higher level data products are generated at payload operation centers (POCs) located at respective payload development centers by the payload managers. The necessary pipeline software resides at the appropriate work centres. Suitable data acquisition and distribution policy are worked out. Necessary public outreach is also planned and being executed.

Figure 6 shows the interface between different ground segment elements and the POCs and users. Since Aditya-L1 is designed as a proposal based observatory, any interested users can put up a science proposal through the Aditya-L1 Proposal Processing System (ALPPS). The payload teams also use this ALPPS for scheduling the observations with an identified configuration. The observation plan, once approved by an identified committee during the science operation phase, will go to the master database which is then used to generate the observation plan and operation schedule before the command is sent to the spacecraft.

After the observations are carried out and during the ground visible period, the data is downloaded from the on board storage. The data are then processed at Level-0 before sending it to the POCs for further levels of science processing.

4.1. Spacecraft Control Centre at the Mission Operation Complex (MOX)

The nerve center for the Aditya-L1 mission will be the spacecraft control center (SCC) located at the mission operation complex (MOX) in ISTRAC campus, Bengaluru. This center is responsible for all spacecraft operations during different mission phases, viz. pre-launch simulations, launch and early orbit phase, Earth-bound operations, trans-L1 injection (TL1I), cruise phase, trajectory correcting manoeuvre (TCM), halo-orbit insertion and normal phase L-1 bound operations. The center is also responsible for spacecraft control and

payload operations. MOX control center is responsible for up linking of the commands for any change in on board configuration, payload operations and execution of orbit manoeuvres as per the mission and science requirements.

4.2. Indian Deep Space Network (IDSN)

Two antennas, 32- and 18-meter diameter (D32 and D18, respectively), located in Bengaluru support the spacecraft TM and science data reception, command, and ranging functions. IDSN campus also houses a technical complex, facility building, and power complex in addition to other infrastructure facilities. The ground stations house independent fully redundant electronics for TTC and science data functions. Cryo-cooled low-noise amplifiers (LNAs), high-performance TTC processors, 2.5 kW X-band high power amplifier (HPA), maser or cesium (Cs) beam based timing/frequency standard systems, CCSDS compatibility, station computers, and space link extension protocols are the highlights of the IDSN. Data services from IDSN will be tailored to interface with the supporting agency interfaces. For Aditya-L1, the D18 will be the prime station and the D32 will act as a back up station for the D18. Also, during any critical operations, the D32 station will also support.

4.3. Network Control Centre (NCC)

All the ground station operations are fully automated and monitored and controlled remotely from a centralized network control centre at Bengaluru, through remote monitoring and control systems.

4.4. Indian Space Science Data Centre (ISSDC)

The Indian Space Science Data Center (ISSDC) located at IDSN campus, Byalalu, Bengaluru, provides payload data management for space science missions which includes raw payload data ingestion, different levels of processing, long-term, and short-term archival, and dissemination of data. ISSDC has a heritage of supporting the missions like AstroSat, Chandrayaan series (Ch-1, Ch-2, and Ch-3), YouthSat, Megha Tropiques, AIS-SB of Resourcesat2, SARAL, and MOM.

ISSDC archives data products that are generated at various levels of payload data management. Apart from this, all the higher-level products generated at POCs and value-added products generated at ISSDC are also archived and backed up.

4.5. Payload Operations Centre (POC)

POCs are responsible for the planning and generation of instrument observation and calibration schedule. They are also authorized to interact with the mission team for the purpose of instrument operation and for obtaining the science data. For Aditya-L1, ISSDC processes the raw data from the spacecraft into a Level-0 (L0) along with auxillary data. POCs receive their respective payload L0 data and process them further to higher level products (Level-1, Level-2, and higher level wherever required). These higher level products including calibration data are then sent to ISSDC for archive and dissemination.

Table 6 Consolidated Earth bound manoeuvres (EBN), the Trans-L1 injection (TLII), and TCM operations to ensure halo-orbit insertion conditions for L1 injection of the spacecraft.

Manoeuvre MVR	Prg No	Burn start time 2023 (UT)	Burn duration (sec)	Delta-V (m/sec)	Prop. (Kg)	Perigee (km)	Apoogee (km)
EBN-1	5	Sep 03, 06:09	357.12	105.127	49.81	249.0	22,379.1
EBN-2	11	Sep 04, 21:00	1191.04	384.658	166.96	286.2	40,058.8
EBN-3	21	Sep 09, 20:39	756.1	272.406	105.88	294.8	71,365.2
EBN-4	26	Sep 14, 20:34	429.57	165.064	60.13	248.2	120,883.2
TLII	28	Sep 18, 20:21	592.26	245.692	83.55	253.3	1,140,445.5
TCM-1	-	Oct 05, 06:30	16.807	2.307	0.88	-	-
Total			3342.897	1175.25	467.21		

4.6. Ground Station Network Support

The ground network is tailored to cater to all phases of the mission to ensure continuous health monitoring, commanding, and tracking data collection. The following list provides the ground station network used for Aditya-L1 mission.

- ISTRAC network stations: SHAR-1, Bengaluru, Port Blair, Brunei, Mauritius, and IDSN.
- ESA network station: The European Space Operations Centre (ESOC), operated by the European Space Agency (ESA) is supporting the mission using their stations at Kourou, Masapalamous, and New Norcia.

5. Aditya-L1 Journey to the Halo Orbit

The Aditya-L1 spacecraft was launched by PLSV-C57 on 2 September 2023 from SDSC SHAR, ISRO, Sriharikota into an elliptical parking orbit (EPO) of 235.6 km by 19,502.7 km to mark a significant step forward in solar observation, aiming to unravel the mysteries of our closest star, the Sun. With this, Aditya-L1 embarks on an extraordinary journey towards the Sun-Earth L1 Lagrange point, a strategic location that offers a unique vantage to study the solar dynamics.

Five planned liquid engine burns (LEB) are executed in Earth orbit phase; gradually raise the apogee of the EPO to attain the desired trans-L1 trajectory with the fifth burn, known as the trans-L1 injection (TLII manoeuvre). The manoeuvre strategy is carefully devised to minimize ΔV in reaching the target L1 halo orbit while restricting the number of perigee passes to minimize the exposure of the spacecraft to the Van Allen radiation belts. To address TLII errors, TCM-1 was conducted on 5 October 2023 and another TCM-2 on 14 December 2023 to ensure compliance with halo-orbit insertion condition parameters. Details of the early phase burns for trans-L1 injection and TCM operations are provided in Table 6.

The spacecraft underwent a cruise phase which lasted for approximately 110 days to achieve the halo-orbit insertion condition on 6 January 2024. The halo-orbit insertion process commences as the spacecraft crosses the XZ plane in the Sun-Earth-L1 rotating system (see Figure 7 for the relevant coordinate system), with the required orbital state. In Sun-Earth L1 phase, the reference frame is the L1 centred synodic frame as given in Figure 7. The insertion manoeuvre is essential to nullify the X and Z velocity components and attain the required Y velocity in the L1 rotating frame for the required halo orbit.

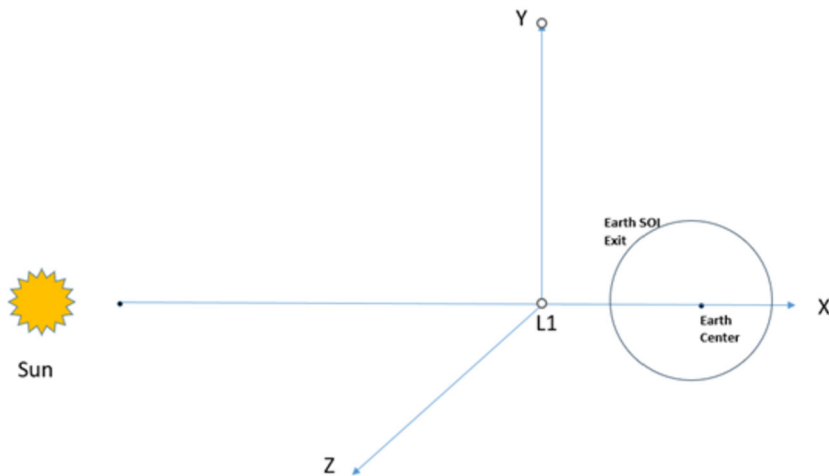


Figure 7 Sun-Earth synodic frame and the coordinate system. Note objects are not to scale.

Table 7 The planned and achieved orbital parameters of Aditya-L1 satellite at L1.

Parameter	After manoeuvre (planned)	After manoeuvre (achieved)
X (km)	245,635.0	245,634.2
Y (km)	-23.2	-20.2
Z (km)	-106,054.9	-106,052.0
V _x (km/s)	-0.000066	-0.000162
V _y (km/s)	-0.298636	-0.298429
V _z (km/s)	0.000020	0.0000925

6. Challenges in Aditya-L1 Mission

6.1. Defining L1 Orbit

A satellite placed at L1 has challenges for both orbit and attitude systems. Modeling of the N-body problem, analysis of stability of periodic orbits around Sun-Earth L1, and selection of halo orbit for Aditya-L1 was finalized considering mission constraints

- Minimum Sun-Earth-satellite angle (solar exclusion zone) to avoid solar interference in communications
- Maximum Sun-Earth-satellite angle to account for antenna FOV/steerability.
- Manoeuvre strategy design and analysis to achieve and maintain the desired halo orbit with minimum ΔV cost and still satisfying operational constraints.

Based on the above constraints, the orbit of Aditya-L1 at the Sun-Earth L1 point was decided. The intended and the achieved orbit parameters, on 6 January 2024 at 10:30:19 UTC on the XY crossing plane at the L1 centre rotating frame coordinate system, are included in the Table 7.

Table 8 Pointing and drift of the satellite estimated from on board observations.

Element	Requirement	Achieved
Pointing	45 arcsec (3σ) (satellite + payload)	36 arcsec (3σ) - estimated using SUI payload
Drift	0.25 arcsec/sec	0.18 arcsec/sec

6.2. Stringent Pointing and Stability Requirement

VELC payload on board Aditya-L1 requires the highest pointing and stability of the spacecraft. The coronagraph images the solar corona and performs spectroscopic observations from $1.05 R_{\odot}$ to $1.5 R_{\odot}$. Given that VELC is an internally occulted coronagraph and has an inner FOV close to 50 arcsec from the solar disk, the pointing needs to be ensured not to introduce large scatter into VELC and also damage the secondary mirror where focused sunlight falls. VELC payload demands a strict pointing of less than 45 arcsec (at a 3σ level) and stability better than 5×10^{-5} deg/s.

The required pointing accuracy is achieved by the high accuracy active pixel Sun sensor (HAPSS), which provides 4 arcsec accuracy along the roll and pitch axes and star sensor which provides 10 arcsec along the yaw axis.

The platform stability is achieved by the inertial referencing and accelerometer package (IRAP) for attitude control using rate sensing and velocity increment measurement in the spacecraft body axis.

Magnetically suspended reaction wheels (MSRW) mounted in tetrahedral configuration are used to minimize the disturbance on the spacecraft. Magnetic bearings used in the MSRW offer high reliability, and show no wear or abrasion over the 5 year mission life.

Table 8 shows the specifications achieved on board Aditya-L1 compared to the highest payload requirements.

6.3. Autonomy and Automation

Autonomy is highly crucial in deep-space missions especially to mitigate latency and non-visibility. Autonomy and automation also:

- Improve the use and efficiency of scientific instruments and enhance management of complexity through rule based algorithms.
- Demand for a thorough verification and validation of software and analysis of potential risk of ambiguity and reliability.
- Normally include continuous watch on major subsystems like sensors, actuators, transponders/transmitter, solar array drive assembly (SADA) for power generation, etc.

Automation is the execution of certain functions automatically. A set of sequences of actions are compiled in perfect order and satisfy constraints. Following on board autonomy, features are enabled and tested in orbit to ensure spacecraft and payload safety:

- VELC M2 mirror, which is placed at the focal point of the primary mirror, can reach a very high temperature in case the solar disk light falls on the mirror due to loss of lock. Temperature based safety enabled closes the VELC door when the M2 mirror temperature is more than a set temperature.
- LEB (liquid engine burn) event automation during orbit raising and halo-orbit insertion.
- Momentum dumping events programmed for door close and high voltage elements are set to off condition during dumping.

- Gyro-false detection, identification, and recovery (FDIR) is enabled.
- Safe mode for the satellite enables the switching off of all payloads during satellite anomaly.

6.4. Contamination Control

Contamination may be simply defined as any unwanted foreign matter which affects the performance of the system under study. In general, contamination is grouped into two broad categories labeled molecular and particulate. No biological contamination is considered for Aditya-L1 mission. Molecular contamination refers to the cumulative buildup of individual molecules of foreign matter. Molecular contamination may occur during ground processing and in the orbit. Particulate contamination refers to the deposition of visible conglomerations of matter. These particles, which are deposited mainly during ground operations, will fall from the air onto exposed surfaces.

Studies reveal that most of the molecular contaminants are more absorptive in the ultra-violet than in the visible or infrared. For this reason, UV payloads are much more sensitive to molecular contamination:

Aditya-L1 spacecraft carries two contamination sensitive payloads and both are prone to degradation due to molecular and particulate contamination.

1. Visible Emission Line Coronagraph (VELC) operated in the visible and IR range
2. Solar Ultraviolet Imaging Telescope (SUIT) operated in the UV range

The following are the measures taken to ensure clean environmental conditions for Aditya-L1 instruments and also for the spacecraft.

- All materials and processes used are subjected to screening processes and based on contamination clearance the material or processes are added to the approved DML/DPL list.
- The materials used in Aditya-L1 are having the total mass loss (TML) of $< 1\%$ and collected volatile condensable materials (CVCM) of $< 0.1\%$
- Cleaning process consists of such operations as vacuuming, dry wiping, solvent wiping, or ultrasonic cleaning, as applicable, to remove shop oils and other contamination.
- Additional high efficiency particulate air (HEPA) filters are installed in the clean room
- All packages are vacuum baked before the delivery to the assembly, integration, and test (AIT) facility

Table 9 shows the protocols followed during different phases of activities at the spacecraft, as well as at the subsystem level.

6.4.1. Particulate Contamination

For the particulate contamination, clean room facilities at the spacecraft integration area were upgraded to Class 10,000 with 100-class clear air modules deployed around the spacecraft. Continuous gaseous nitrogen purging was carried out after the assembly of payloads on the satellite. At the subsystem level, VELC payload was integrated in Class 10 area and SUIT payload was integrated in Class 100 area.

Table 10 shows the cleanliness achieved at the spacecraft integration area during the satellite integration and testing phase.

Table 9 Contamination control implementation summary.

Sl. no.	Implementation phase	Method of implementation
1.	Design phase	Material selection and design for cleanability.
2.	Fabrication phase	Cleaning, vacuum baking, and inspection.
3.	Vacuum baking phase	Cleaning of tested hardware, as applicable prior to vacuum baking, installation of temperature controlled quartz crystal microbalance (TQCM) inside the vacuum chamber, placement of magnesium fluoride (MgF2) windows/ optical window samples (OWS) as applicable. Packaging with cleaned electro static discharge (ESD) protective sheet wrapping/ gaseous nitrogen (GN2) purged ESD covers.
4.	Storage phase	Storing the baked, packaged hardware in storing cabinets.
5.	Assembly/test phase (payload/subsystem level) and assembly, integration, and test phase (spacecraft level)	Clean room upgrading, filter modules deployment, handling, gowning as per protocol, airborne particulate monitoring, particle fall out (PFO) monitoring, bi-directional reflection distribution function (BRDF) measurements, OWS placement and purging of payloads using ultra high pure (UHP) GN2, as applicable.
6.	Spacecraft level environmental tests	Cleaning of facilities, filter modules deployment, vacuum baking of thermo vacuum chamber (TVAC) facility and monitoring using MgF2/OWS/TQCM as applicable inspection of facilities and spacecraft, purging of payloads using UHP GN2 as applicable.
7.	Containerization and de-containerization	Cleaning of container, bagging and removal of bagging, airborne particulate monitoring, placement of PFO plate, MgF2/OWS window inside the container, purging of payloads.
8.	Spacecraft preparation-2 (SP-2) phase	Cleaning of facilities, filter modules deployment, airborne particulate monitoring, monitoring using PFO plate and MgF2/OWS window, purging of payloads.
9.	Mobile service tower (MST) phase	Cleaning of facilities, airborne particulate monitoring, monitoring using PFO plate, MgF2/OWS window, purging of payloads till heatshield closure. Fairing with filtered cooled air.
10.	Temporary launch delay	Circulation of filtered cooled air.
11.	Long launch delay and heat shield opening	Containerization and protocols as per Sl. No. 9.

6.4.2. Molecular Contamination

In order to minimize the molecular contamination, vacuum baking of all flight hardware is carried out. The protocols are developed to use the AstroSat mission and ASTM E2900 standard. The baking temperature is kept 10 degrees above the maximum operating temperature of each of the subsystems.

For the VELC payload level TVAC tests, the molecular level contamination measured was less than 1.05×10^{-10} g/cm²/sec when the TVAC shroud was at -10 degree Celsius.

Table 10 Particulate cleanliness maintained at the spacecraft integration duration.

Contaminant type	Specifications	Achieved
Airborne particulate	10,000 Class	375 to 9983 particles/cubic-feet of air in the assembly and integration area.
Surface particulate using PFO (mm ² /m ²)	9100 PFO	After arrival of payloads 2700 (from 17-3-2023) and 5700 (since 18-7-2022)

**Figure 8** Sub-system level Magnetic Field Measurement Facility (SSMFMF) used to measure all subsystem magnetic field. A model was built to estimate the total spacecraft level magnetic field.

For the SUIT payload, the measured values were 1.6×10^{-12} g/cm²/sec when the shroud was at -100 degree Celsius. During the spacecraft level tests, the contamination level measured was 2.1×10^{-12} g/cm²/sec. MgF₂ coupons were kept for VELC and SUIT payloads during different phases of operations at the payload as well as the spacecraft levels. The total transmission loss measured was less than 2% in the wavelength range of 130 nm to 180 nm.

While the VELC payload provides the expected throughput over the last 1.5 years of operation, SUIT payload has seen reduction in throughput due to contaminants settling in the detector which is the coldest location within the optical cavity. However, the expected throughput is recovered after baking of the detector. Currently, a process is placed for SUIT payload to ensure that the baking is enabled before the throughput reduces to an unacceptable level.

6.5. Magnetic Field Measurement

The Magnetometer payload is intended to measure the interplanetary magnetic field (IMF), at the first Lagrangian point, L1. The nominal IMF at L1 is expected to be of the order of 5 to 10 nT, under solar quiet condition and may go up to 50 nT, and above during high solar activity. In order to measure the magnetic field at L1, a dual sensor is used in differential mode to eliminate the spacecraft bias field. The dual sensor is mounted at the 3 m and 6 m away from the spacecraft using a 6 m long boom. The accuracy of in situ measurements of weak magnetic field, like IMF is limited by the spacecraft generated field and the stability of the zero level of the magnetometers.

The mitigation followed in the spacecraft to reduce the residual field are:

- Magnetically clean solar array which uses solar cells with silver interconnects and silver busbar. A special wiring technique has been implemented to minimize the current carrying loop.

- To reduce the magnetic field generated in the battery, current loop is reduced by placing positive and negative bus bars (at the centre) as close as possible. Also, positive and negative wires are twisted to avoid current loops.
- Subsystem level magnetic field measurement facility (SSMFMF) is established at ISITE-URSC, Bengaluru, to measure the magnetic field generated by individual subsystem.
- The total spacecraft static and dynamic dipole fields at the magnetometer sensor location are calculated using the subsystem magnetic moment measurement (see Figure 8). The magnetic moment of all the forty-two subsystems is determined using the SSMMF (see Figure 8). These magnetic moment values are then used in the magnetic field model of the spacecraft (GAMAG software) with proper position and orientation of the 3D magnetic topology around the spacecraft which shows the dipole nature of the resultant spacecraft magnetic field.

The spacecraft magnetic fields were estimated using the subsystem magnetic moment measurements and calculated the expected field at the location of the sensor in Aditya-L1 using the GAMAG software. The estimated and the measured magnetic field difference at the 3 m and 6 m sensor are 16% and 9%, respectively (Table 9 of Yadav et al. 2025). These measurements are carried out at the stowed condition.

6.6. Ground Station Visibility

Earth visibility, for L1, is restricted to about 12 hours for every Earth station. This calls for on board automation for control of attitude and orbit. Built-in automatic safe mode is enabled for Aditya-L1 to protect payload and satellite health in case of anomaly. External ground station support was taken during critical operations.

7. Summary

The Aditya-L1 mission is unique in its capabilities. The mission is expected to probe the dynamics of coronal mass ejections (CMEs) close to the solar disk at $1.05 R_{\odot}$. This would provide very valuable information about the so far unobserved acceleration regime of the CME. The mission also has for the first time, a near ultra-violet (NUV) full disk imager to provide observations relevant for spatially resolved irradiance from the solar disk. This would allow to identify the structures on the Sun in contributing to the irradiance variation over different temporal and spatial scales. The mission also captures information on the energy distribution, flux and directionality of the solar wind and energetic particles. This would enable studies relevant to space weather and would enable identifying parameters of importance for forecasting. Aditya-L1 would also provide uninterrupted solar flare studies in a wide energy band providing observational data to fill the void left by the decommissioning of the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI) mission.

Aditya-L1 was launched on 2 September 2023 by PSLV-C57 into an elliptical orbit (EPO) of 235.6 km by 19,502.7 km from SDSC SHAR, ISRO, Sriharikota and inserted into the final halo orbit on 6 January 2024. Currently (December 2024), Aditya-L1 completed two L1 halo orbits and venture into its 3rd orbit. The payload verification phase of all payloads is completed and they are currently in the science operation phase. The data pipeline needed for all the payloads are met and the regular flow of data from the POCs to ISSDC is initiated. Dissemination of science ready data is planned in the year 2025 from the ISSDC.

Aditya L1 mission is expected to provide several new discoveries and expand our knowledge of CMEs and other eruptive phenomena occurring on the Sun. It is also expected to

provide better understanding of important dynamics of Sun, including CMEs and insights to science aspects of space weather events.

Acknowledgments Aditya-L1 satellite is designed and developed by the U R Rao Satellite Centre (URSC), Indian Space Research Organization. To achieve this, various centres of ISRO and entities within URSC immensely contributed. VSSC provided the launcher and SDSC SHAR enabled the launch of Aditya-L1. For the spacecraft: Thermal Systems Group provided the required thermal design, analysis and implementation support; Mechanism Group developed the required mechanisms and integrated them into the relevant subsystems; Systems Integration Group helped in the structural analysis of the subsystems and satellite and actively participated in the integration, vibration and shock tests; Reliability and Quality Assurance Group ensured that all non-space grade components are qualified or up-screened for its reliability and quality; Assembly and Integration Team took the responsibility of integrating the subsystems and payloads to the satellite; Mission and Flight Dynamics Group helped in the mission as well as trajectory aspects of Aditya-L1, L0 data generation for the payloads including the required HK and SPICE data of Aditya-L1, and day-to-day operation of the mission; Indian Space Science Data Centre (ISSDC) and ISRO Satellite Tracking centre (ISTRAC) are the nodal point of data downloading from the spacecraft and communication with the subsystems and Payload Operation Centre (POC), they will be the dissemination centre for the science ready data; Aditya-L1 Project Team coordinated the overall activities as a nodal point.

Aditya-L1 is an observatory class mission which is fully funded and operated by the Indian Space Research Organization. The mission was conceived and carried out with the help from all ISRO Centres and payloads were carried out by the payload PI Institutes in close collaboration with ISRO and many other national institutes: Indian Institute of Astrophysics (IIA); Inter-University Centre of Astronomy and Astrophysics (IUCAA); Laboratory for Electro-Optics System (LEOS) of ISRO; Physical Research Laboratory (PRL); U R Rao Satellite Centre of ISRO; Vikram Sarabhai Space Centre (VSSC) of ISRO.

The authors thank the anonymous referee and the editor for very useful comments and suggestions which improved the paper significantly.

Author Contributions Nigar Shaji is the Project Director for Aditya-L1 (AL1), Nashiket Premal Parate is the Deputy Project Director for overall systems of AL1, K. Sankarasubramanian is the Principal Scientist of AL1, Motamarri Srikanth is the Mission Director for AL1, all others are Deputy Project Directors for different subsystems of AL1.

Data Availability No datasets were generated or analyzed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

References

- Arunan, S., Satish, R.: 2015, Mars orbiter mission spacecraft and its challenges. *Curr. Sci.* **109**, 1061.
- Goyal, S.K., Tiwari, N.K., Patel, A.R., Shanmugam, M., Vadawale, S.V., Chakrabarty, D., Sebastian, J., Dalal, B., Sharma, P., Sarkar, A., Sarda, A., Ladiya, T., Verma, A.J., Singh, N., Kumar, S., Painkra, D.K., Kumar, P., Shah, M.S., Adhyaru, P.R., Adalja, H.L., Banerjee, S.B., Subramanian, K.P., Bapat, B., Dadhanian, M.B., Kumar, A., Janardhan, P., Bhardwaj, A.: 2025, Aditya solar wind particle experiment on board Aditya-L1: the supra-thermal and energetic particle spectrometer. *Sol. Phys.* **300**, 35. DOI: ADS.
- Janardhan, P., Vadawale, S., Bapat, B., Subramanian, K.P., Chakrabarty, D., Kumar, P., Sarkar, A., Srivastava, N., Satheesh Thampi, R., Yadav, V.K., Dhanya, M.B., Nampoothiri, G.G., Abhishek, J.K., Bhardwaj, A., Subhalakshmi, K.: 2017, Probing the heliosphere using in situ payloads on-board Aditya-L1. *Curr. Sci.* **113**, 620. DOI: ADS.
- Kumar, P., Bapat, B., Shah, M.S., Adalja, H.L., Patel, A.R., Adhyaru, P.R., Shanmugam, M., Chakrabarty, D., Banerjee, S.B., Subramanian, K.P., Sarkar, A., Ladiya, T., Sebastian, J., Kumar, A., Kumar, S., Singh, N., Dadhanian, M.B., Vadawale, S.V., Goyal, S.K., Tiwari, N.K., Sarda, A., Painkra, D.K., Sharma, P., Verma, A.J., Yogesh, J.P., Bhardwaj, A.: 2025, Aditya solar wind particle experiment (ASPEX) on board Aditya-L1: the solar wind ion spectrometer (SWIS). *Sol. Phys.* **300**, 37. DOI: ADS.
- Nandi, A., et al.: 2025, HELIOS - A Hard X-ray Spectrometer on Board Aditya-L1. *Sol. Phys.*, in press.

- Raghavendra Prasad, B., Banerjee, D., Singh, J., Nagabhushana, S., Kumar, A., Kamath, P.U., Kathiravan, S., Venkata, S., Rajkumar, N., Natarajan, V., Juneja, M., Somu, P., Pant, V., Shaji, N., Sankarabramanian, K., Patra, A., Venkateswaran, R., Adoni, A.A., Narendra, S., Haridas, T.R., Mathew, S.K., Mohan Krishna, R., Amareswari, K., Jaiswal, B.: 2017, Visible emission line coronagraph on Aditya-L1. *Curr. Sci.* **113**, 613. DOI. ADS.
- Raju, G.: 2013, Engineering challenges in the Megha-Tropiques satellite. *Curr. Sci.* **104**, 1662.
- Sankarasubramanian, K., Ramadevi, M.C., Bug, M., Umaphathy, C.N., Seetha, S., Sreekumar, P.: 2011, Kumar: SoLEXS - a low energy X-ray spectrometer for solar coronal studies. In: *Astronomical Society of India Conference Series, Astronomical Society of India Conference Series* **2**, 63. DOI. ADS.
- Sankarasubramanian, K., Bug, M., Sarwade, A., Sharan, V., Kumar, K.A., Verma, S., Ramadevi, M.C., Lakshminpathaiah, K., Thakur, M.K., Gupta, K., Sharma, N., Justin, E.L., Narendra, S., Adoni, A., Srikanth, M., Subramanian, V., Sahu, S.N., Pai, V.K., Mustafa, S.F., Parate, N., Shamrao, Dey, A., T. S., Upadhyay, P., T. R., Malhotra, G., Satyanarayana, S.V., Thejasree, M., S. M., G S, N.R., Patra, B.K., Maiya, S., A. L., A. R., Shivam, K., Purohit, A.: 2025a, Solar low energy X-ray spectrometer (SoLEXS) on board Aditya-L1 mission. *Sol. Phys.* **300**, 87. DOI. ADS.
- Sankarasubramanian, K., Chakrabarty, D., Nandi, A.K., Satheesh Thampi, R., Jagdev, S., Tripathi, D., Yadav, V.K.: 2025b, Synergy and potential science from co-ordinated observations with Aditya-L1 and other observatories. In: *Synergetic Science from Space and Ground Based Assets, IAU Symposium Series, IAU Symposium Under Review*.
- Seetha, S., Megala, S.: 2017, Aditya-L1 mission. *Curr. Sci.* **113**, 610. DOI. ADS.
- Singh, J., Ramesh, R., Prasad, B.R., Priyal, V.M., Raja, K.S., Venkata, S.N., Kamath, P.U., Natarajan, V., Pawankumar, S., Krishnan, V.U.S., Savarimuthu, P., Mishra, S., Kumar, V., Sumana, C., Hegde, S.B., Utkarsha, D., Kumar, A., Nagabhushana, S., Kathiravan, S., Vemareddy, P., Kathiravan, C., Nagaraju, K., Ravindra, B., Mishra, W.: 2025, Visible emission line coronagraph (VELC) on board Aditya-L1. *Sol. Phys.* **300**, 66. DOI. ADS.
- Thampi, R.S., Abhishek, J.K., Sasidharan, D., Varma, G., Sen, V.K., Ray, S., Dhanya, M.B., Pandey, U., Chandra, S.K.S., Akash, J.B., Aneesh, A.N., Wilson, T.M., Naresh, S., Naik, N., Yadav, M.C., Venkataraman, V., John, R., Manoj, R., Nampoothiri, G.G., Meshram, P., George, M., Ramdas, V., George, G.V., Pillai, A.M., Dey, A., Das, S., Varier, G.S., Sajitha, G., Mathews, S., Kumar, P.P., Nisha, G.R., Nandi, A., Sundar, B., Sethunadh, R., Rajendra, A., Saleem, H., Samad, A.K.A.: 2025, Plasma-analyzer package for Aditya (PAPA) on board the Indian Aditya-L1 mission. *Sol. Phys.* **300**, 9. DOI. ADS.
- Tripathi, D., Ramaprakash, A.N., Khan, A., Ghosh, A., Chatterjee, S., Banerjee, D., Chordia, P., Gandorfer, A., Krivova, N., Nandy, D., Rajarshi, C., Solanki, S.K.: 2017, The solar ultraviolet imaging telescope on-board Aditya-L1. *Curr. Sci.* **113**, 616. DOI. ADS.
- Tripathi, D., Ramaprakash, A.N., Padinhateeri, S., Sarkar, J., Burse, M., Tyagi, A., Kesharwani, R., Sinha, S., Joshi, B., Deogaonkar, R., Roy, S., Nived, V.N., Gopalakrishnan, R., Kulkarni, A., Khan, A., Ghosh, A., Rajarshi, C., Modi, D., Kumar, G., Yadav, R., Varma, M., Bayanna, R., Chordia, P., Karmakar, M., Abraham, L., Adithya, H.N., Adoni, A., Ahmed, G.A., Banerjee, D., Bhargava Ram, B.S., Bhandare, R., Chatterjee, S., Chillal, K., Dey, A., Gandorfer, A., Gowda, G., Haridas, T.R., Jain, A., James, M., Jayakumar, R.P., Justin, E.L., Nagaraju, K., Kathait, D., Khodade, P., Kiran, M., Kohok, A., Krivova, N., Kumar, N., Mehandiratta, N., Mestry, V., Motamarri, S., Mustafa, S.F., Nandy, D., Narendra, S., Navle, S., Parate, N., Pillai, A.M., Punnadi, S., Rajendra, A., Ravi, A., Raha, B., Sankarasubramanian, K., Sarvar, G., Shaji, N., Sharma, N., Singh, A., Singh, S., Solanki, S.K., Subramanian, V.: 2025, The solar ultraviolet imaging telescope on board Aditya-L1. *Sol. Phys.* **300**, 30. DOI. ADS.
- Valarmathi, N., Tyagi, R.N.: 2013, RISAT-1 spacecraft configuration: architecture, technology and performance. *Curr. Sci.* **104**, 462.
- Yadav, V.K., Vijaya, Y., Krishnam Prasad, B., Srikar, P.T., Mahajan, M., Mallikarjun, K.V.L.N., Zamani, S.N., Satyanarayana Kumari, B., Lohar, K.A., Kandpal, M.M., Narendra, S., Rai, V.S., Adoni, A.A., Veerasha, D.R., T.S., S., Kalpana, A., Srivastava, N., Vichare, G.: 2025, The fluxgate magnetometer (MAG) on board Aditya-L1 spacecraft. *Sol. Phys.* **300**, 33. DOI. ADS.

Authors and Affiliations

Nashiket Premal Parate¹ · Nigar Shaji¹ · Motamarri Srikanth¹ ·
K. Sankarasubramanian^{1,2} · Narashimha Murthy Patnaik¹ · S. Narendra¹ ·
Abhijit Avinash Adoni¹ · Kuldeep Negi¹ · Pragyan Pattanaik¹ · Bharat Kumar G. V. P¹ ·
Vivek R. Subramanian¹ · Hemanth Kumar Reddy N.¹ · Shree Niwas Sahu¹ ·
Vishnu Kishore Pai¹ · Sajjade Faisal Mustafa¹ · Richa Pathak³ · Amit Maji⁴ ·
T.R. Haridas⁵ · Anand Raj⁶ · Pankaj Agarwal⁷ · Arvind Kumar Singh¹ ·
Smruti Ranjan Panigrahi¹ · A. Ravi¹

✉ K. Sankarasubramanian
sankark@urisc.gov.in

¹ U R Rao Satellite Centre, Indian Space Research Organization, Bengaluru, Karnataka, India

² CESSI, IISER-Kolkatta, Kolkatta, West Bengal, India

³ Liquid Propulsion Systems Centre (LPSC), Bengaluru, Karnataka, India

⁴ Laboratory for Electro-optics Systems (LEOS), Bengaluru, Karnataka, India

⁵ ISRO Inertial Systems Unit (IISU), Thiruvananthapuram, Kerala, India

⁶ ISRO Telemetry, Tracking and Command Network (ISTRAC), Bengaluru, Karnataka, India

⁷ Composites Entity (CMSE), Vikram Sarabhai Space Science Centre (VSSC), Thiruvananthapuram, Kerala, India